

4. Tungsten Ribbon Filament Lamp Calibrations

4.1 Lamp preparation

Tungsten ribbon filament lamps are calibrated by NIST for the temperature range 800 EC to 2300 EC in terms of the 1990 NIST Radiance Temperature Scale by spectral comparison to a standard temperature lamp calibrated at 655.3 nm. New lamps are inspected for filament continuity, envelope and window clarity, and filament flatness and centering. A digital multimeter is used to check the filament continuity. The envelope or window is checked for defects and striations in the optical path. The filament is checked to determine that it is flat, parallel to the envelope walls, and within 2 mm of being centered in the envelope or window. The lamps are cleaned with water and laboratory glassware detergent.

Test lamps (TL) are operated base down on direct current with the center contact (longer filament support for a bipost base lamp) at the positive potential. The test lamps are tested for air leaks by turning the lamp on, then off, and then on again after 15 min. If air has leaked into the lamp envelope because of bad or broken seals, then the lamp will fail when it is turned on. Lamps that pass the leak test are annealed to improve lamp stability. New gas lamps are annealed at a radiance temperature of 2350 EC at 655.3 nm for 2 h on direct current and vacuum lamps are annealed at 1450 EC for about 14 h. The gas lamps are aged for an additional 50 h at 2300 EC.

The lamp orientation chosen for the calibration of a new lamp minimizes the variation in lamp output while maintaining the optical axis of the measuring instrument approximately normal to the lamp filament. This orientation is determined with the lamp operating at approximately 1700 EC for a gas lamp, or 1200 EC for a vacuum lamp. An arrow is etched onto the rear surface of the lamp envelope to allow reproducible alignment of this orientation. The alignment is performed with the lamp operating base down, the filament vertical, and the optical axis of the PEP passing through the lamp envelope and intersecting the center of the filament at the height of the notch. The sides of the target area, area 0.6 mm wide by 0.8 mm high, are approximately parallel to the sides of the lamp filament. The center of the target area is located at the intersection of two orthogonal lines on the filament surface. One line bisects the filament lengthwise, and the other passes through the point centered at the mouth of the notch. The lamp is positioned so that the etched arrow on the lamp envelope is to the rear, as viewed from the PEP. The center of the target area is viewed along the horizontal optical axis of the PEP. A plumb line is used to make the notch side of the filament vertical. The image of the lamp filament is focused onto the field stop of the PEP to within "2.5 mm. The lamp is then successively rotated about the horizontal and vertical centerlines through the target area until the tip of the arrowhead is centered at the mouth of the notch.

4.2 Lamp calibration

The values of radiance temperature apply when the lamp has been aligned to a specified orientation while operating at a designated radiance temperature and after the lamp has reached thermal stability at each specified operating current. The WS and TL are aligned as described in Section 4.1 at one temperature. At all other temperatures, the TL is translated vertically and/or horizontally so that the target area viewed by the PEP is always centered on the lamp filament at the height of the notch. No additional rotational alignments are performed

The initial lamp current that corresponds to 1700 °C is selected from previous data for the

lamp type. The TL is turned on and set to approximately 1700 °C and aligned after 30 min. The spectral radiance ratio of the TL to the WS, r_2 , is calculated, the WS signal, S_{WS2} , is measured, and the TL signal, S_{TL} , that corresponds to 1700 °C is calculated. The lamp current is adjusted until the measured signal is equal to S_{TL} . After waiting 10 min, the final alignment of the TL and the WS is performed and the TL is spectrally compared to the WS to determine its radiance temperature. The spectral radiance ratio of the TL to the WS is measured three times by alternately translating the WS and the TL to the PEP. If the percent standard deviation of the ratio is less than the control limit, then the next calibration point is measured; otherwise, the point is repeated. The control limits are equal to the relative standard uncertainty ($k = 1$) of the ratio and were determined from previous calibration data. The control limits are the expected uncertainties for the spectral radiance ratio measurement. Next, the TL is aligned and measured at 2300 EC after waiting 20 min. The additional calibration temperatures are aligned and measured in decreasing order after waiting 10 min. A typical calibration interval is 100 EC. The following temperatures are repeated at the previously determined lamp currents to estimate the lamps stability: 1700 EC, 2300 EC, 1900 EC, 1500 EC, 1100 EC, and 800 EC. The following data is stored in a computer file: nominal temperature, measured temperature, lamp current, and spectral radiance ratio. See the “Ribbon Filament Lamp Calibration Procedure” in Appendix D for a more details on lamp calibrations in the RTLC.

4.3 Lamp data analysis

The repeated calibration temperatures are averaged and the standard error of the mean is calculated and compared to the absolute control limits. These results are used to determine the expanded uncertainties listed in the calibration report.

Calibration data is reported at the nominal temperatures 800 EC, 900 EC, 1000 EC, ... 2300 EC. One method to determine the nominal temperatures is to measure it directly. Through an iterative process, the TL is repeatedly measured and the lamp current is adjusted until the nominal temperature is actually measured. However, the RTCL calculates the lamp current that corresponds to the nominal temperature from measurements of the measured temperature (T_m) near the nominal temperature (T_n).

For a small ΔT , where $\Delta T = T_n - T_m$, the small change in lamp current is approximated by the slope of the tangent at T and given by

$$\frac{dI(T)}{dT} = \lim_{\Delta T \rightarrow 0} \frac{\Delta I}{\Delta T} = \lim_{\Delta T \rightarrow 0} \frac{I(T + \Delta T) - I(T)}{\Delta T} . \quad (35)$$

This limit simplifies to a working equation of the form

$$I(T + \Delta T) = I(T) + \frac{dI}{dT} \cdot \Delta T , \quad (36)$$

where $I(T)$ is the measured lamp current I_m at T_m and $I(T + \Delta T)$ is the measured lamp current I_{corr} . The derivative dI/dT can be approximated by $\Delta I/\Delta T$, which can be modeled as

$$\frac{\Delta I}{\Delta T} = \sum_{j=0}^5 a_j T_{\text{mean}}^j . \quad (37)$$

The coefficients a_j are calculated from a least squares fit of two other parameters, T_{mean} and $\Delta I/\Delta T$. The first parameter is defined by

$$T_{\text{mean}} = \frac{T_{m,k} + T_{m,k+1}}{2} , \quad (38)$$

and the slope of the line between the calibration points P_k and P_{k+1} in figure 22 is given by

$$\frac{\Delta I}{\Delta T} = \frac{I_{m,k} - I_{m,k+1}}{T_{m,k} - T_{m,k+1}} . \quad (39)$$

Figure 22 shows the shape of the curve for T_m versus I_m . $\Delta I/\Delta T(T_{\text{mean}})$ is fit to a fifth degree polynomial giving the coefficients a_j . Figure 23 shows the shape of the curve with of T_{mean} and $\Delta I/\Delta T$ used to calculate the coefficients a_j . From eq (36), the corrected lamp current is

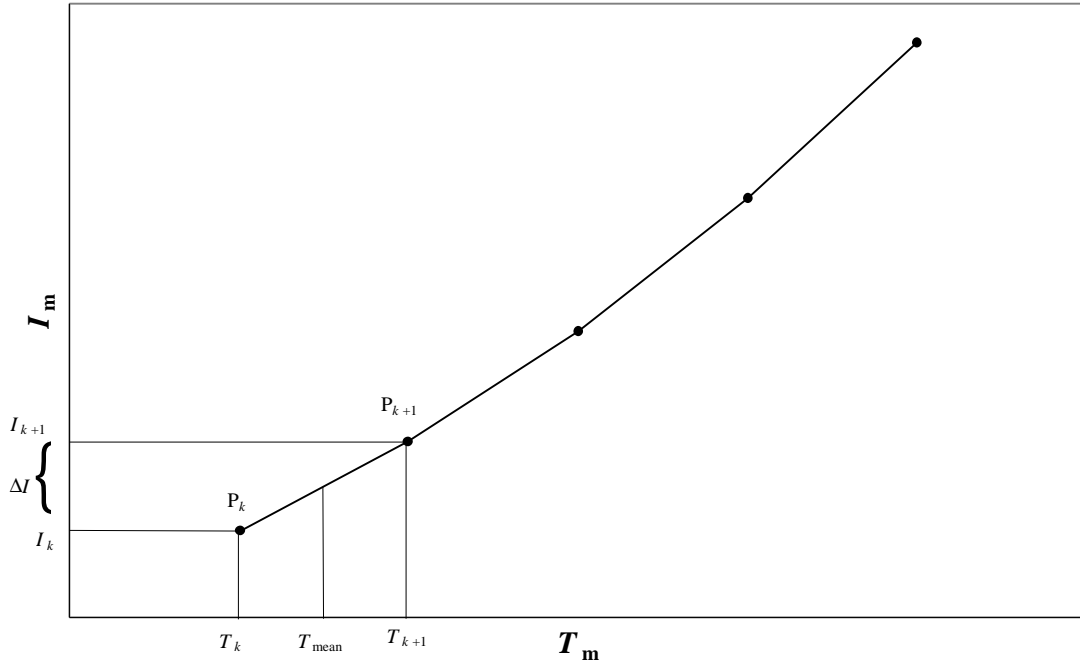


Figure 22. Calculation of I_{corr} from T_{mean} and $\Delta I/\Delta T$.

determined to be

$$I_{\text{corr}} = I_{\text{m}} + \frac{dI}{dT} (T_{\text{n}} - T_{\text{m}}) . \quad (40)$$

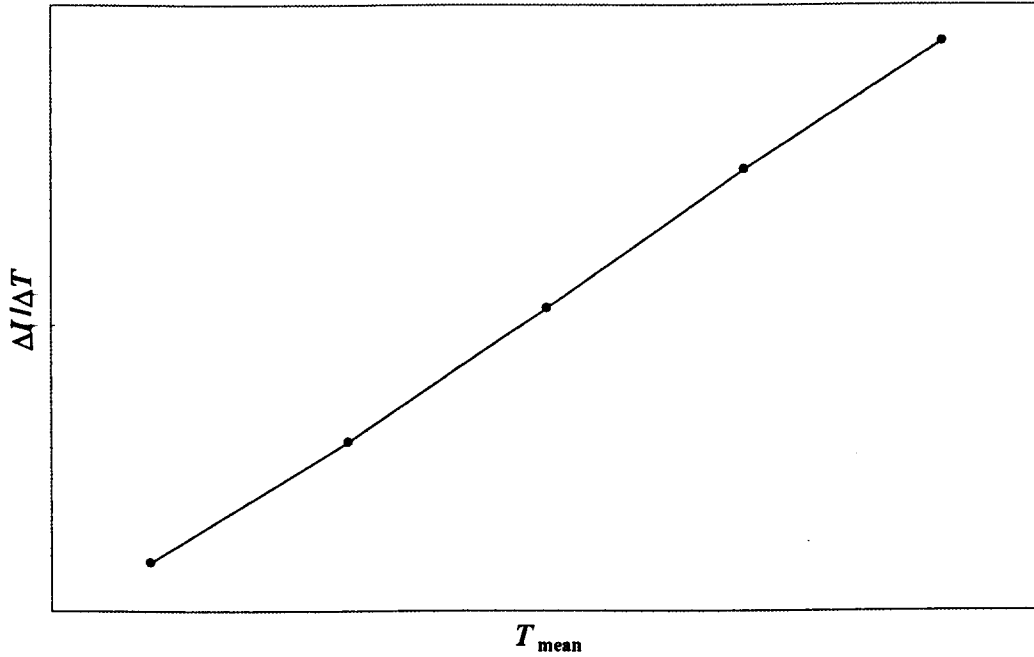


Figure 23. Graph of T_{mean} and $\Delta I/\Delta T$.

A least squares fit of the entire calibration data sets finds the best curve for the data set but not necessarily for each data point. This method ensures that the direction of the correction is right and has been verified by comparison to the iterative method. Sample data can be found in the “Ribbon Filament Lamp Data Reduction Procedure” in Appendix D.

4.4 Lamp calibration uncertainty

To calibrate test lamps (TL), the ratio (r_2) of the spectral radiance of the WS lamp to that of the TL,

$$r_2 = \frac{L_{\lambda}(T_{\text{TL}})}{L_{\lambda}(T_{\text{WS2}})} = \frac{S_{\text{TL}}}{S_{\text{WS2}}} , \quad (41)$$

is first measured. Taking into account the correction factors for the signals, the overall measurement equation for the 1990 NIST Scale of Radiance Temperature for calibration of the TL temperature is

$$T_{\text{TL}} = \frac{c_2}{n_I \cdot I \cdot \ln \left[1 + \frac{\mathbf{e}_{I,\text{TL}} \cdot c_{1L}}{n_I^2 \cdot I^5 \cdot L_{\text{WS2}} \cdot r_2} \frac{(C_A \cdot C_L \cdot C_S \cdot G)_{\text{WS}}}{(C_A \cdot C_L \cdot C_S \cdot G)_{\text{TL}}} \right]}. \quad (42)$$

In a manner similar to eq (28), the uncertainty in the spectral radiance of the WS can be represented by the RSS of products of partial derivatives,

$$u_0(T_{\text{TL}}) = \left[\left(\frac{\partial T_{\text{TL}}}{\partial n_I} \cdot u(n_I) \right)^2 + \left(\frac{\partial T_{\text{TL}}}{\partial I} \cdot u(I) \right)^2 + \left(\frac{\partial T_{\text{TL}}}{\partial c_2} \cdot u(c_2) \right)^2 + \sum_{i=1}^{12} \left(\frac{\partial T_{\text{TL}}}{\partial x_i} \cdot u(x_i) \right)^2 \right]^{1/2}, \quad (43)$$

where x_i is one of the variables: \mathbf{e}_{TL} , c_{1L} , L_{WS} , r_2 , $C_{A,\text{WS}}$, $C_{L,\text{WS}}$, $C_{S,\text{WS}}$, G_{WS} , $C_{A,\text{TL}}$, $C_{L,\text{TL}}$, $C_{S,\text{TL}}$, or G_{TL} . The partial derivatives of T_{TL} with respect to n_I , I , and c_2 are

$$\frac{\partial T_{\text{TL}}}{\partial n_I} = \frac{T_{\text{TL}}}{n_I} \cdot \left[\frac{\mathbf{e}_{I,\text{TL}} \cdot c_{1L}}{n_I^2 \cdot I^5 \cdot L_{\text{WS2}}} \cdot \frac{2 \cdot \frac{(C_A \cdot C_L \cdot C_S \cdot G)_{\text{WS}}}{(C_A \cdot C_L \cdot C_S \cdot G)_{\text{TL}}}}{r_2 \cdot \frac{c_2}{n_I \cdot I \cdot T_{\text{TL}}} \cdot \exp\left(\frac{c_2}{n_I \cdot I \cdot T_{\text{TL}}}\right)} - 1 \right], \quad (44)$$

$$\frac{\partial T_{\text{TL}}}{\partial I} = \frac{T_{\text{TL}}}{I} \cdot \left[\frac{\mathbf{e}_{I,\text{TL}} \cdot c_{1L}}{n_I^2 \cdot I^5 \cdot L_{\text{WS2}}} \cdot \frac{5 \cdot \frac{(C_A \cdot C_L \cdot C_S \cdot G)_{\text{WS}}}{(C_A \cdot C_L \cdot C_S \cdot G)_{\text{TL}}}}{r_2 \cdot \frac{c_2}{n_I \cdot I \cdot T_{\text{TL}}} \cdot \exp\left(\frac{c_2}{n_I \cdot I \cdot T_{\text{TL}}}\right)} - 1 \right], \text{ and} \quad (45)$$

$$\frac{\partial T_{\text{TL}}}{\partial c_2} = \frac{T_{\text{TL}}}{c_2}. \quad (46)$$

The partial derivatives of T_{TL} with respect to x are

$$\left| \frac{\partial T_{\text{TL}}}{\partial x} \right| = \frac{T_{\text{TL}}}{x} \cdot \frac{\mathbf{e}_{\text{I,TL}} \cdot c_{1L}}{n_1^2 \cdot \mathbf{I}^5 \cdot L_{\text{WS2}}} \cdot \frac{\frac{(C_A \cdot C_L \cdot C_S \cdot G)_{\text{WS}}}{(C_A \cdot C_L \cdot C_S \cdot G)_{\text{TL}}}}{r_2 \cdot \frac{c_2}{n_1 \cdot \mathbf{I} \cdot T_{\text{TL}}} \cdot \exp\left(\frac{c_2}{n_1 \cdot \mathbf{I} \cdot T_{\text{TL}}}\right)}, \quad (47)$$

where x is one of the variables labeled x_i in eq (43).

Typical values of the variables in eq (42) are shown in table 9, and the uncertainties of eq (43) are displayed in table 10. The total expanded relative uncertainty $u(T_{\text{TL}})/T_{\text{TL}}$ in the TL temperature has contributions from $u_0(T_{\text{TL}})$ in eq (43), from the uncertainty $u(\text{TLC})$ in the TL current, and from the uncertainty $u(\text{AL})$ in alignment. These contributions are shown in table 10 and are summed by the RSS technique as follows,

$$\frac{u(T_{\text{TL}})}{T_{\text{TL}}} = \left[\left(\frac{u_0(T_{\text{TL}})}{T_{\text{TL}}} \right)^2 + \left(\frac{u(\text{TLC})}{T_{\text{TL}}} \right)^2 + \left(\frac{u(\text{AL})}{T_{\text{TL}}} \right)^2 \right]^{1/2}. \quad (48)$$

From tables 9 and 10, a typical relative expanded uncertainty in the TL temperature realization is 1.10 K/1973.52 K, or about 0.059 %. For other nominal TL temperatures besides 1700 EC, the user is referred to table 2.

Table 9. Typical values of TL variables and parameters

Variable	Symbol	Value
Refractive index	n_1	1.00028
Wavelength	\mathbf{I}	655.3 nm
Second radiation constant	c_2	14387.69 $\mu\text{m} \cdot \text{K}$
Emissivity of TL	\mathbf{e}_{TL}	1
First radiation constant	c_{1L}	$1.191 \times 10^8 \text{ W} \cdot \mu\text{m}^4 \cdot \text{m}^{-2}$
WS spectral radiance	L_{WS}	$569.9 \text{ W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1} \cdot \text{sr}^{-1}$
Ratio of TL signal to WS signal	r_2	2.551
WS amplifier calibration correction	$C_{\text{A,WS}}$	0.09986
WS linearity correction	$C_{\text{L,WS}}$	1
WS size of source correction	$C_{\text{S,WS}}$	1
WS amplifier gain	G_{WS}	$1 \times 10^9 \text{ V} \cdot \text{A}^{-1}$
TL amplifier calibration correction	$C_{\text{A,TL}}$	1
TL linearity correction	$C_{\text{L,TL}}$	1
TL size of source correction	$C_{\text{S,TL}}$	1
TL amplifier gain	G_{TL}	$1 \times 10^8 \text{ V} \cdot \text{A}^{-1}$
TL temperature	T_{TL}	1973.52 K

Table 10. Uncertainty budget for the TL temperature calibration

Uncertainty component	Symbol	Expanded Uncertainty ($k = 2$)	
		Type A	Type B
Refractive index	$u(n_I)$		0.00002
Wavelength	$u(I)$		0.2 nm
Second radiation constant	$u(c_2)$		0.24 $\mu\text{m}\cdot\text{K}$
Emissivity of TL	$u(e_{\text{TL}})$		0.0002
First radiation constant	$u(c_{1\text{L}})$		440 $\text{W}\cdot\mu\text{m}^4\cdot\text{m}^{-2}$
WS spectral radiance	$u_0(L_{\text{WS}})$		2.998 $\text{W}\cdot\text{m}^{-2}\cdot\mu\text{m}^{-1}\cdot\text{sr}^{-1}$
Ratio of TL signal to WS signal	$u(r_2)$	0.0051	
WS amplifier calibration correction	$u(C_{\text{A,WS}})$	0.00001	
WS linearity correction	$u(C_{\text{L,WS}})$	0.001	
WS size of source correction	$u(C_{\text{S,WS}})$	0.0002	
WS amplifier gain	$u(G_{\text{WS}})$		0 $\text{V}\cdot\text{A}^{-1}$
TL amplifier calibration correction	$u(C_{\text{A,TL}})$	0.0001	
TL linearity correction	$u(C_{\text{L,TL}})$	0.001	
TL size of source correction	$u(C_{\text{S,TL}})$	0.0002	
TL amplifier gain	$u(G_{\text{TL}})$		0 $\text{V}\cdot\text{A}^{-1}$
TL temperature	$u_0(T_{\text{TL}})$		1.10 K
TL current	$u(\text{TLC})$	0.09 K	
Alignment	$u(\text{AL})$	0.30 K	
TL temperature calibration	$u(T_{\text{TL}})$		1.10 K